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14. ABSTRACT
A significant amount of theoretical work on dilute atomic BEC has focused on how condensates interact with ultra-cold charged impurities. To enable experimental studies, we have constructed a BEC setup embedded in a Faraday cage suitable to compensate stray electric fields at the BEC location to levels below about 0.1 mV/cm. Using RF-induced evaporative cooling and evaporative cooling by surface adsorption we prepare atom clouds down to one microKelvin temperature. Cold ions have been created using two-step photo-ionization of magnetically trapped cold atom clouds. The ions have been extracted using the electric field of a tip close to the atom clouds, and they have been detected using a channel-plate detector. Ion imaging capability has been demonstrated by generating tomographic cuts of small cold atom clouds. Electric-field compensation routines based on Rydberg-atom spectroscopy have been experimentally tested. To date, the electric field has been compensated to about 1mV/cm. Work to increase the initial atom number is in progress. An atomic-beam shutter intended to reduce the vacuum pressure in the BEC chamber has been designed and is being tested. The work has lead to several peer-reviewed publications on BECs in optical lattices.

15. SUBJECT TERMS

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Final progress report:

Recently, a significant amount of theoretical work on dilute atomic BEC has focused on how condensates interact with ultra-cold charged impurities. The phenomena one may expect to find include the formation of mesoscopic molecular ions via recombination of BEC atoms into ion-induced polarization potentials, ion-induced structures in the BEC wave-function, quantum charge diffusion, and self trapping of ions in BECs. To enable experimental studies of these topics, we have constructed a BEC setup embedded in a Faraday cage suitable to compensate stray electric fields at the BEC location to levels below about 100 microvolt/cm.

In preparation of the ion-BEC work, we have conducted several experiments on the interaction between Bose–Einstein condensates (BECs) with optical lattices.

1) We have experimentally realized an atom cavity consisting of a magnetic trap and an optical lattice that extends over the whole trap. When displaced sufficiently from the center of the magnetic trap, dynamics of the atoms are characterized by magnetic confinement on one side of the cavity and Bragg reflection due to the optical lattice on the other side. We demonstrate this atom cavity by recording the momentum-space oscillation of a Bose-Einstein condensate inside the cavity as a function of time. This atom-cavity configuration presents the possibility of realizing a Mach-Zehnder-type atom interferometer. The work was published in "Bose-Einstein condensate inside a Bragg-reflecting atom cavity," R. Zhang, R. E. Sapiro, N. V. Morrow, R. R. Mhaskar, and G. Raithel, Phys. Rev. **A 77**, 063615 – 1-5 (June 2008).

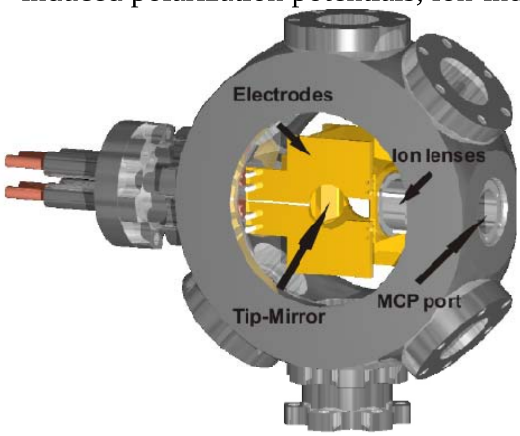
2) Using the Crank-Nicholson method, we have studied the evolution of a Bose-Einstein condensate in an optical lattice and harmonic trap. The condensate is excited by displacing it from the center of the harmonic trap. The mean field plays an important role in the Bloch-type oscillations that occur after sufficiently large initial displacement. We found that a moderate mean field significantly suppresses the dispersion of the condensate in momentum space. When the mean field becomes large, soliton and vortex structures appear in the condensate wave function. The work was published in "Role of the mean field in Bloch oscillations of a Bose-Einstein condensate in an optical lattice and harmonic trap", R. Zhang, R. E. Sapiro, R. R. Mhaskar, G. Raithel, Phys. Rev. **A 78**, 053607 – 1 - 7 (Nov. 2008).

3) We have applied a one-dimensional (1D) optical lattice, formed by two laser beams with a wavelength of 852 nm, to a three-dimensional 87Rb BEC in a shallow magnetic trap. We have used Kapitza–Dirac scattering to determine the depth of the optical lattice. A qualitative change in behavior of the BEC has been observed at a lattice depth of 30 recoil energies, where the quantum gas has undergone a reversible transition from a superfluid state to a state that lacks well-to-well phase coherence. These observations are consistent with a 1D Mott insulator transition, but can also be explained by mean-field effects. The work has been published ["Reversible loss of superfluidity of a Bose-Einstein condensate in a 1D optical lattice," R. E. Sapiro, R. Zhang and G. Raithel, New J. Phys. **11**, 013013 (10) (2009)].

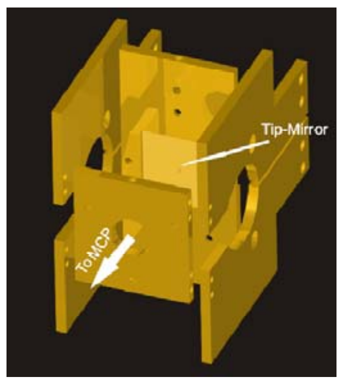
4) We have demonstrated two atom interferometric schemes based on Kapitza-Dirac scattering in a magnetic trap. In the first method, two Kapitza-Dirac scattering pulses are applied with a small time delay between them. High contrast interference is observed both using a thermal cloud and a BEC. In the second method, two Kapitza-Dirac scattering pulses are applied to a BEC with a

time separation sufficiently large that the interfering orders complete half an oscillation in the magnetic trap; this enables interferometry between spatially separated paths. The work has been published ["Atom interferometry using Kapitza-Dirac scattering in a magnetic trap," R.E. Sapiro, R. Zhang, and G. Raithel, Phys. Rev. **A 79**, 043630-6 (2009)].

The second half of the grant period was mostly spent with the implementation of a setup suitable for the study of interactions between a BEC and low-energy ions. This topic has been the subject of a significant amount of recent theoretical work. The phenomena one may expect to find include the formation of mesoscopic molecular ions via recombination of BEC atoms into ion-induced polarization potentials, ion-induced structures in the BEC wave-function, quantum charge diffusion, and self trapping of ions in BECs. To enable experimental studies of these topics, we have constructed a BEC setup embedded in a Faraday cage (see figure) suitable to compensate stray electric fields at the BEC location to levels below about 100 microvolt/cm. Under such conditions, the ion dwell time in the BEC will reach about 100 microseconds, which should be sufficient to observe the above phenomena. We are not, at present, planning to implement an active surface Paul-type ion trap, because the role of the ion micro-motion in such traps has unknown effects on the overall system dynamics.

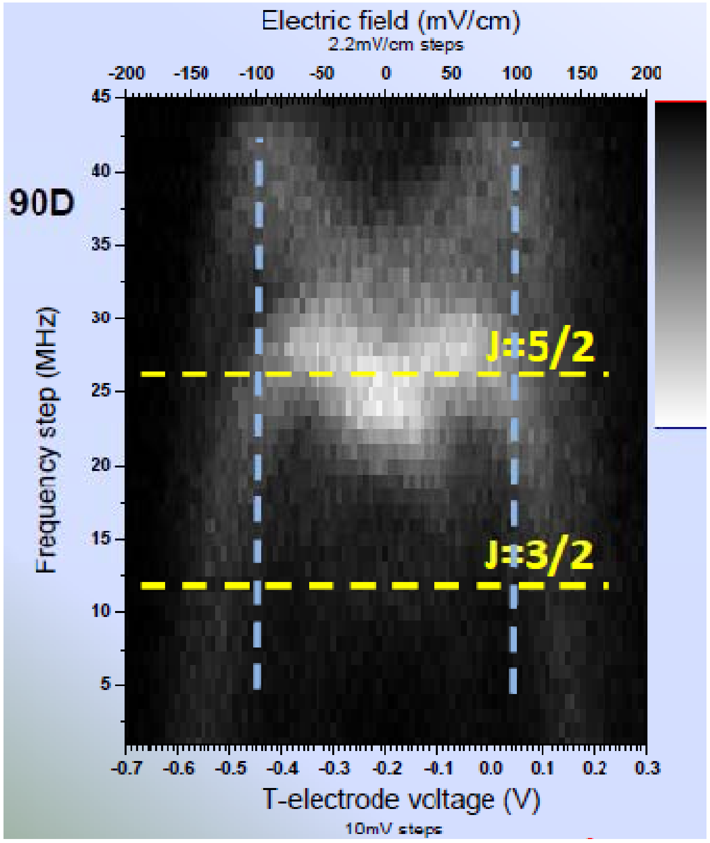


BEC chamber overview

Electrode cage


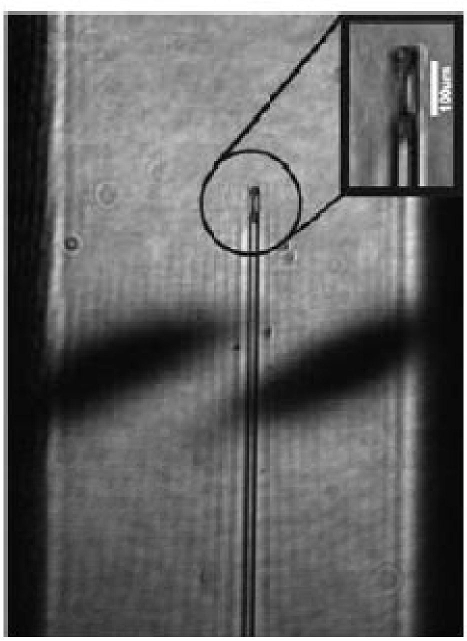
The BEC setup is based on the quite well known U-trap/Z-trap scheme. RF-induced evaporative cooling has been demonstrated down to about one microKelvin temperature. The RF is injected through the Z-wire. We also have evaluated the method of evaporative cooling by surface adsorption.

Cold ions have been created using two-step photo-ionization of magnetically trapped cold atom clouds. The ions have been extracted using the electric field of a "tip" close to the atom clouds, and they have been detected using a channel-plate detector. The "tip" consists of a point-like electrode that has been micro-fabricated into an in-vacuum mirror that is part of the BEC setup. Since the tip is only about 1mm away from the ion location, large magnification factors for the ion images can be achieved.



The electric-field-control hardware for the Faraday cage has been installed and a Labview software package has been developed. Electric-field compensation routines based on Rydberg-atom spectroscopy have been experimentally tested.

←Field compensation using the Stark effect of Rb 90D Rydberg levels. The figure shows Rydberg line positions in MHz vs. the voltage applied to one of the compensation electrodes. The symmetry line of the figure marks the voltage that corresponds to zero electric field. To zero the electric-field vector, the procedure is applied three times for electrodes addressing all orthogonal field components.



← Magnetic trapping in front of extraction electrode. The figure shows an image of the ion extraction patch electrode (diameter 100μm) seen in a shadow image of a 35μK magnetically trapped atom cloud. The patch electrode is electrically isolated from the larger electrode/mirror chip on which it sits. Note the lead wire connecting to it from below. The image was taken by a reflection of the shadow imaging beam off the chip surface at 10 degree grazing-incidence, showing both the real atom cloud (right) and its reflection (left).

The project has provided support for several graduate students, two of which have graduated (Rahul Mhaskar, Rui Zhang) and one (David Anderson) who has advanced to candidacy.